



EUROPEAN UNION



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“Investing in Sustainable Development”



Prompt gamma rays from the spontaneous fission of ^{252}Cf and their angular distributions

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Outline

- Introduction
- Experimental setup
- Data treatment
- Preliminary results
- Discussion
- Summary & outlook

Introduction

- For many years: precise measurement of prompt fission γ -ray spectra (PFGS)

Introduction

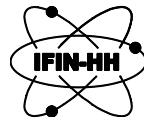


- For many years: precise measurement of prompt fission γ -ray spectra (PFGS)
- Determination of characteristics:
 - $\langle M_\gamma \rangle$, $\langle \varepsilon_\gamma \rangle$, and $\langle E_{\gamma, \text{tot}} \rangle$

Introduction

- For many years: precise measurement of prompt fission γ -ray spectra (PFGS)
- Determination of characteristics:
 - $\langle M_\gamma \rangle$, $\langle \varepsilon_\gamma \rangle$, and $\langle E_{\gamma, \text{tot}} \rangle$
 - Studies of the dependence of A, Z, and E_x

Introduction



PFGS characteristics as function of A, Z and E_x

Cf 239 ~ 39 s α ; 7,63	Cf 240 1,06 m α ; 7,59 sf	Cf 241 3,78 m ϵ ; α ; 7,342	Cf 242 3,68 m α ; 7,392; 7,358 ϵ ? γ	Cf 243 10,7 m ϵ α ; 7,06; 7,17 g	Cf 244 19,4 m ϵ α ; 7,137... g	Cf 245 43,6 m ϵ α ; 7,209; 7,174 g	Cf 246 35,7 h α ; 6,750; 6,708... sf γ ; (42; 96...) e-; g	Cf 247 3,11 h ϵ α ; 6,296; 6,238 sf γ ; (294; 448; 418...); e-; g	Cf 248 333,5 d α ; 6,258; 6,217... sf γ ; (43); e-; g	Cf 249 350,6 a α ; 5,812; 5,758... sf γ ; 388; 333...; g σ ; 500; σ ; 1700	Cf 250 13,08 a α ; 6,030; 5,989... sf γ ; (43...); e-; g σ ; 2000; σ ; < 350	Cf 251 898 a α ; 5,679; 5,849; 6,012... sf γ ; 177; 227... σ ; 2900; σ ; 4500	Cf 252 2,645 a α ; 6,118; 6,076... sf γ ; (43...); e- σ ; 20; σ ; 32
Bk 238 144 s ϵ β sf		Bk 240 5 m ϵ β sf		Bk 242 7 m ϵ sf ?	Bk 243 4,5 h ϵ sf ?	Bk 244 4,35 h ϵ sf ?	Bk 245 4,90 d ϵ sf ?	Bk 246 1,80 d ϵ sf ?	Bk 247 1380 a ϵ sf ?	Bk 248 23,7 h ϵ sf ?	Bk 249 320 d β^- 0; 1; α ; 5,419; 5,391...; sf γ ; (327; 308...); g σ ; 700; σ ; 0,1	Bk 250 3,217 h β^- 0; 1; β 18...; γ ; 989; 1032; 1029...; σ ; 1000	Bk 251 55,6 m β^- ~ 0.9; 1,1... γ ; 178; 130; 153...
	Cm 238 2,4 h ϵ α ; 6,52	Cm 239 3 h ϵ γ ; 188... g	Cm 240 27 d ϵ sf ?	Cm 241 32,8 d ϵ sf ?	Cm 242 162,94 d ϵ sf ?	Cm 243 29,1 a ϵ sf ?	Cm 244 18,10 a ϵ sf ?	Cm 245 8500 a ϵ sf ?	Cm 246 4730 a ϵ sf ?	Cm 247 1,56 - 10 ⁷ a ϵ sf ?	Cm 248 3,40 - 10 ⁵ a ϵ sf ?	Cm 249 64,15 m β^- 0.9... sf γ ; 634; (560; 369...); e- α ; 1,6	Cm 250 ~ 9700 a ϵ β ?; β ? σ ; 80
Am 236 4,4 m ϵ α ; 6,41	Am 237 73,0 m ϵ α ; 6,042 γ ; 280; 436; 474; 909	Am 238 1,63 h ϵ α ; 5,94 γ ; 903; 919; 561; 905... g	Am 239 11,9 h ϵ sf ?	Am 240 50,8 h ϵ sf ?	Am 241 432,2 a ϵ sf ?	Am 242 141 a - 16 h ϵ sf ?	Am 243 7370 a ϵ sf ?	Am 244 26 m - 16 h ϵ sf ?	Am 245 2,05 h ϵ sf ?	Am 246 25 m - 10,1 h ϵ sf ?	Am 247 2,05 h ϵ sf ?		154
Pu 235 25,3 m ϵ α ; 5,85 γ ; 49; (756; 34...); e-	Pu 236 2,858 a ϵ sf ?	Pu 237 45,2 d ϵ sf ?	Pu 238 87,74 a ϵ sf ?	Pu 239 2,411 - 10 ⁴ a ϵ sf ?	Pu 240 6563 a ϵ sf ?	Pu 241 14,35 a ϵ sf ?	Pu 242 3,750 - 10 ⁵ a ϵ sf ?	Pu 243 4,956 h ϵ sf ?	Pu 244 8,00 - 10 ⁷ a ϵ sf ?	Pu 245 10,5 h ϵ sf ?	Pu 246 10,85 d β^- σ ; 150	Pu 247 2,27 d β^-	
Np 234 4,4 d ϵ ; β^+ ... γ ; 1559; 1528; 1602... σ ; 900	Np 235 396,1 d ϵ ; 5,025; 5,007... γ ; (26; 84...); e- g; σ ; 160 + ?	Np 236 225 h ϵ ; 1,54 - 10 ⁸ a ϵ sf ?	Np 237 2,144 - 10 ⁸ a ϵ sf ?	Np 238 2,117 d β^- 1,2... β^- 0; 4; 0,7... γ ; 984; 1029; 1026; 924...; e- g; σ ; 2100	Np 239 2,355 d β^- 0; 4; 0,7... γ ; 106; 278; 228...; e- g; σ ; 32 + 19; σ ; 1	Np 240 7,22 m - 65 m β^- 2,2... β^- 0; 4; 0,7... γ ; 178; 208; 597... e- g; σ ; 2100	Np 241 13,9 m β^- 1,3... β^- 0; 4; 0,7... γ ; 175; (133...); g	Np 242 2,2 m - 5,5 m β^- 1,7... β^- 0; 4; 0,7... γ ; 178; 208; 597... e- g; σ ; 1473	Np 243 1,85 m β^- 0; 4; 0,7... γ ; 288 g	Np 244 2,29 m β^- γ ; 217; 681; 163; 111... g	Np 245 1,85 m β^- γ ; 307; 560; 308...; g		152
U 233 1,592 - 10 ⁵ a α ; 4,824; 4,783... Ne 25; γ ; (42; 97...); e- σ ; 47; σ ; 530	U 234 0,0055 α ; 4,775; 4,723...; sf γ ; 94; Ne; 58; Mg; 25; σ ; 53,121... ϵ ; 96; σ ; < 0,005	U 235 0,7200 ϵ ; 0,07 γ ; 1783 σ ; 0,02	U 236 120 ns - 2,342 - 10 ⁷ a ϵ ; 4,494... β^- 0; 2... γ ; 60; 208... σ ; 100; σ ; < 0,35	U 237 6,75 d ϵ ; 4,445... β^- 0; 2... γ ; 49; 113... σ ; 5,1	U 238 99,2745 ϵ ; 4,468 - 10 ⁵ a β^- 1,2; 1,3... γ ; 75; 44... σ ; 22; σ ; 15	U 239 23,5 m β^- 0; 4... γ ; 44; (190...); e- m	U 240 14,1 h β^- 0; 4... γ ; 44; (190...); e- m	U 242 16,8 m β^- γ ; 68; 58; 585; 573... m		compound systems			

Introduction

PFGS characteristics as function of A, Z and E_x

Cf 239 ~ 39 s α ; 7,63	Cf 240 1,06 m α ; 7,59 sf	Cf 241 3,78 m ϵ ; α ; 7,342	Cf 242 3,68 m α ; 7,392; 7,358 ϵ ? γ ?	Cf 243 10,7 m ϵ ; α ; 7,06; 7,17 g	Cf 244 19,4 m ϵ ; α ; 7,137... g	Cf 245 43,6 m ϵ ; α ; 7,209; 7,174 g	Cf 246 35,7 h α ; 6,750; 6,708... sf γ ; (42; 96...); e-; g	Cf 247 3,11 h ϵ ; α ; 6,296; 6,238 sf γ ; (294; 448; 418...); e-; g	Cf 248 333,5 d α ; 6,258; 6,217... sf γ ; (388; 333...); g ϵ ; (43); e-; g	Cf 249 350,6 a α ; 5,812; 5,758... sf γ ; (388; 333...); g ϵ ; (43); e-; g	Cf 250 13,08 a α ; 6,030; 5,989... sf γ ; (327; 308...); σ 2000; m < 350	Cf 251 898 a α ; 5,679; 5,849; 6,012... sf γ ; (177; 227...); γ (43); e-; g		
Bk 238 144 s ϵ ; β sf		Bk 240 5 m ϵ ; α ; sf		Bk 242 7 m ϵ ; α ; sf	Bk 243 4,5 h ϵ ; α ; sf	Bk 244 4,35 h ϵ ; α ; sf	Bk 245 4,90 d ϵ ; α ; sf	Bk 246 1,80 d ϵ ; α ; sf	Bk 247 1380 a ϵ ; α ; sf	Bk 248 23,7 h β ; α ; sf	Bk 249 320 d β ; α ; sf	Bk 250 3,217 h β ; α ; sf	Bk 251 55,6 m β ; ~ 0.9; 1,1... γ 178; 130; 153...	
	Cm 238 2,4 h ϵ ; α ; 6,52	Cm 239 3 h ϵ ; α ; 188... g	Cm 240 27 d ϵ ; α ; sf	Cm 241 32,8 d ϵ ; α ; 6,291; 6,248... g	Cm 242 162,94 d ϵ ; α ; 6,113; 6,069... g	Cm 243 29,1 a ϵ ; α ; 5,785; 5,742... g	Cm 244 18,10 a ϵ ; α ; 5,805; 5,762... g	Cm 245 8500 a ϵ ; α ; 5,961; 5,304... g	Cm 246 10000 a ϵ ; α ; 4,870; 5,267... g	Cm 247 1,56 - 107 a ϵ ; α ; 4,870; 5,267... g	Cm 248 10000 a ϵ ; α ; 4,870; 5,267... g	Cm 249 64,15 m β ; 0.9... γ 634; (560; 369...); e- σ 1,6	Cm 250 ~ 9700 a ϵ ; α ; ?; β ; ? σ = 80	
Am 236 4,4 m ϵ ; α ; 6,41	Am 237 73,0 m ϵ ; α ; 6,042... γ 280; 436; 474; 909... g	Am 238 1,63 h ϵ ; α ; 5,94... γ 903; 919; 561; 905... g	Am 239 11,9 h ϵ ; α ; 5,774... γ 278; 228... g	Am 240 50,8 h ϵ ; α ; 5,378... γ 988; 889... g	Am 241 432,2 a ϵ ; α ; 5,486; 5,443... γ 60; 26... σ 100; m 270; α ; 3,1	Am 242 141 a ϵ ; α ; 5,491; 5,446... γ 149; 100...; e- σ 100; m 270; α ; 3,1	Am 243 7370 a ϵ ; α ; 5,275; 5,233... γ 75; 44... σ 100; m 270; α ; 0,74	Am 244 7370 a ϵ ; α ; 5,275; 5,233... γ 75; 44... σ 100; m 270; α ; 0,74	Am 245 26 m ϵ ; α ; 5,361; 5,304... γ 75; 133... σ 60; m 82	Am 246 25 m ϵ ; α ; 5,275; 5,233... γ 75; 133... σ 60; m 82	Am 247 2,05 h ϵ ; α ; 5,275; 5,233... γ 75; 133... σ 60; m 82	Am 248 22 m ϵ ; α ; 5,275; 5,233... γ 75; 133... σ 60; m 82	154	
Pu 235 25,3 m ϵ ; α ; 5,85... γ 49; (756; 34...) g	Pu 236 2,858 a ϵ ; α ; sf	Pu 237 45,2 d ϵ ; α ; 5,334... γ 148; 109...; e- σ 1230	Pu 238 87,74 a ϵ ; α ; sf	Pu 239 2411 - 10 ⁴ a ϵ ; α ; 5,499; 5,456... γ 5; Mg 26... γ 143; 100...; e- σ 510; α ; 752	Pu 241 14,35 a ϵ ; α ; sf	Pu 242 14,35 a ϵ ; α ; sf	Pu 243 4,956 h ϵ ; α ; sf	Pu 244 8,00 - 10 ⁷ a ϵ ; α ; sf	Pu 245 8,00 - 10 ⁷ a ϵ ; α ; sf	Pu 246 10,85 d ϵ ; α ; sf	Pu 247 2,27 d ϵ ; α ; sf			
Np 234 4,4 d ϵ ; β ; α ; 1602... γ 1559; 1528; 900	Np 235 396,1 d ϵ ; α ; 5,025... γ 26; 84...; e- σ 160 + ?	Np 236 225 m ϵ ; α ; 5,007... γ (26; 84...); e- σ 160 + ?	Np 237 2,144 - 10 ⁶ a ϵ ; α ; 5,007... γ 160...; e- σ 160 + ?	Np 239 2,355 d ϵ ; α ; 4,790; 4,774... γ 29; 67...; e- σ 180; α ; 0,020	Np 240 7,22 m ϵ ; α ; 4,790; 4,774... γ 106; 278... σ 32 + 19; m < 1	Np 241 13,9 m ϵ ; α ; 4,794; 4,774... γ 175; (133...); g	Np 242 2,2 m ϵ ; α ; 4,794; 4,774... γ 175; (133...); g	Np 243 1,85 m ϵ ; α ; 4,794; 4,774... γ 175; (133...); g	Np 244 2,29 m ϵ ; α ; 4,794; 4,774... γ 217; 681; 163; 111... g	Np 245 2,29 m ϵ ; α ; 4,794; 4,774... γ 217; 681; 163; 111... g	Np 246 10,85 d ϵ ; α ; sf	Np 247 2,27 d ϵ ; α ; sf	152	
U 233 1,592 - 10 ⁵ a α ; 4,824; 4,783... Ne 25; γ 42; 97...; e- σ 42; α ; 530	U 234 0,0055... ϵ ; α ; sf	U 235 0,7200 ϵ ; α ; sf	U 236 26 m ϵ ; α ; sf	U 237 6,75 d ϵ ; α ; sf	U 238 99,2745 ϵ ; α ; sf	U 239 270 ns ϵ ; α ; sf	U 240 14,1 h ϵ ; α ; sf	U 242 16,8 m ϵ ; α ; sf	compound systems					

(n, f)  previous work
 upcoming work

(sf)  previous work

Introduction

The Co-workers

Introduction

The Co-workers

Quote: “It started as a family business... now it's
a "gang" ;-)"

Patrick Talou, July 6, 2017

Introduction

“The Gang”

T. Belgia, R. Billnert, R. Borcea, T. Brys, A. Chatillon, D. Choudhury, S. Courtin, M. Fallot, G. Fruet, A. Gatera, W. Geerts, G. Georgiev, A. Göök, C. Guerrero, P. Halipré, F.-J. Hambsch, D.G. Jenkins, Z. Kis, B. Laurent, M. Lebois, L. Le Meur, A. Maj, P. Marini, B. Maróti, T. Martinez, I. Matea, A. Moens, L. Morris, V. Nanal, P. Napiorkowski, A. Porta, F. Postelt, A. Oberstedt, S. Oberstedt, L. Qi, L. Szentmiklosi, K. Takàcs, S. J. Rose, G. Sibbens, S. Siem, C. Schmitt, O. Serot, M. Stanoi, D. Vanleeuw, M. Vidali, B. Wasilewska, J.N. Wilson, A.-A. Zakari, F. Zeiser ...

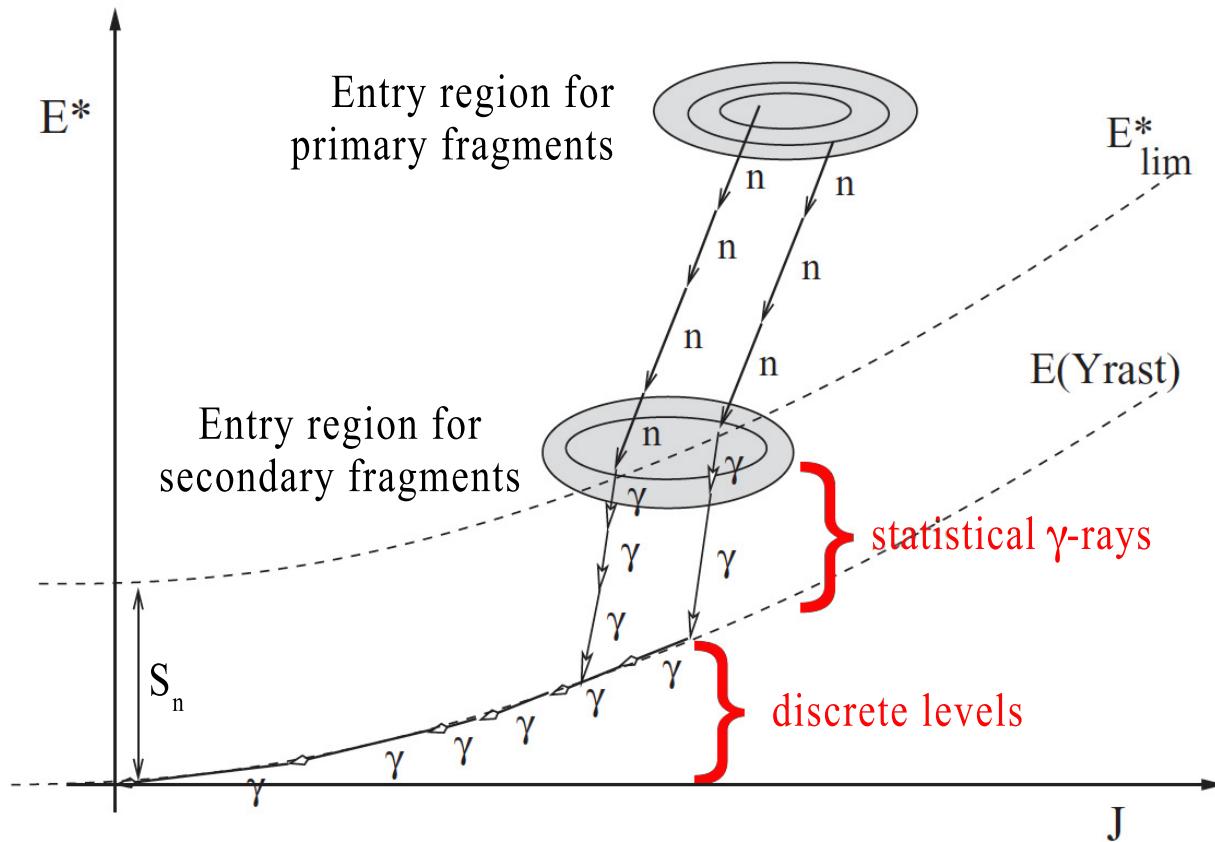
PhD students

Introduction

- For many years: precise measurement of prompt fission γ -ray spectra (PFGS)
- Determination of characteristics:
 - $\langle M_\gamma \rangle$, $\langle \varepsilon_\gamma \rangle$, and $\langle E_{\gamma, \text{tot}} \rangle$
 - Studies of the dependence of A, Z, and E_x
 - Now: focus on the de-excitation process of fission fragments

Introduction

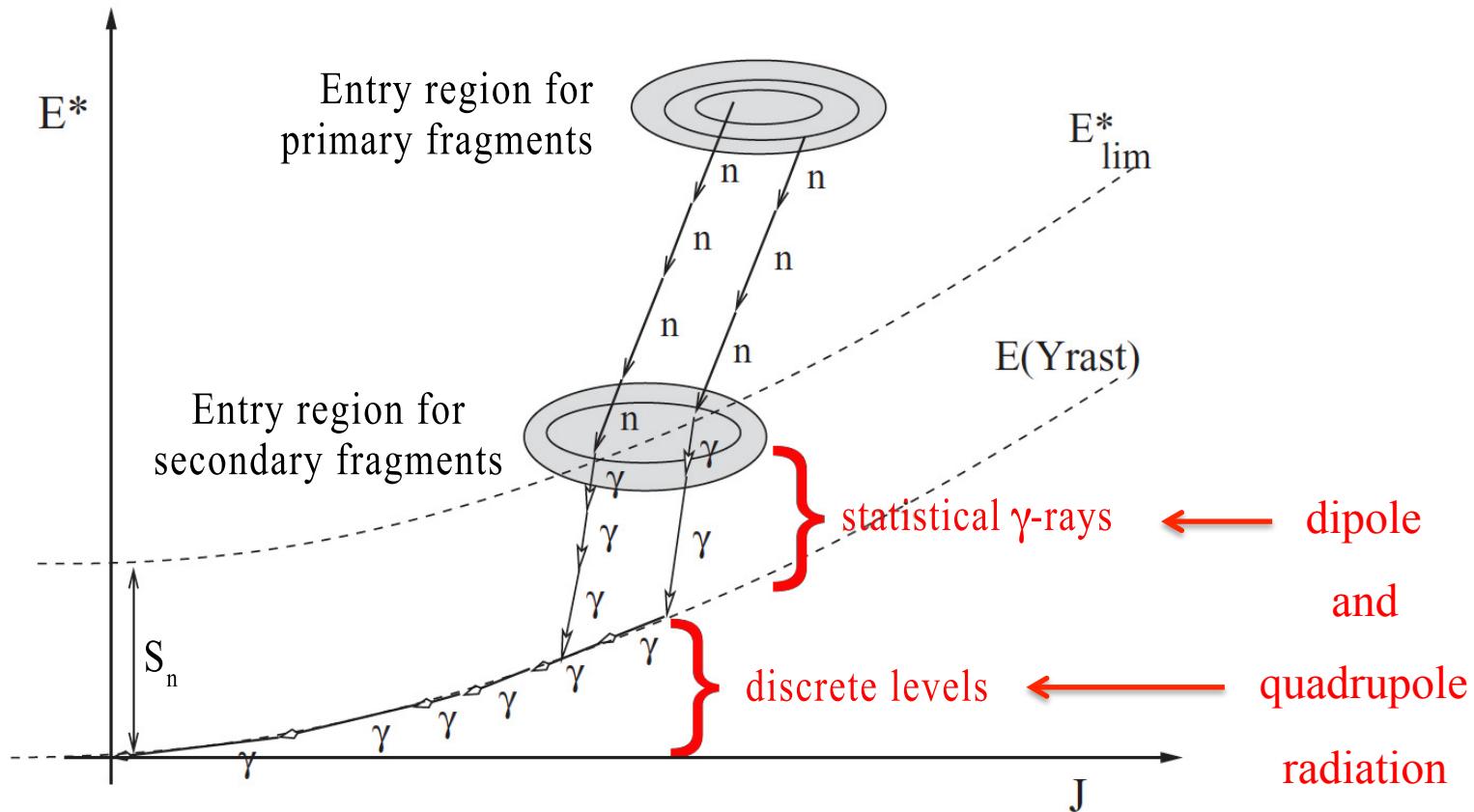
Sequential emission of neutrons and γ -rays



According to: Litaize & Serot, PRC 82, 054616 (2010)

Introduction

Sequential emission of neutrons and γ -rays



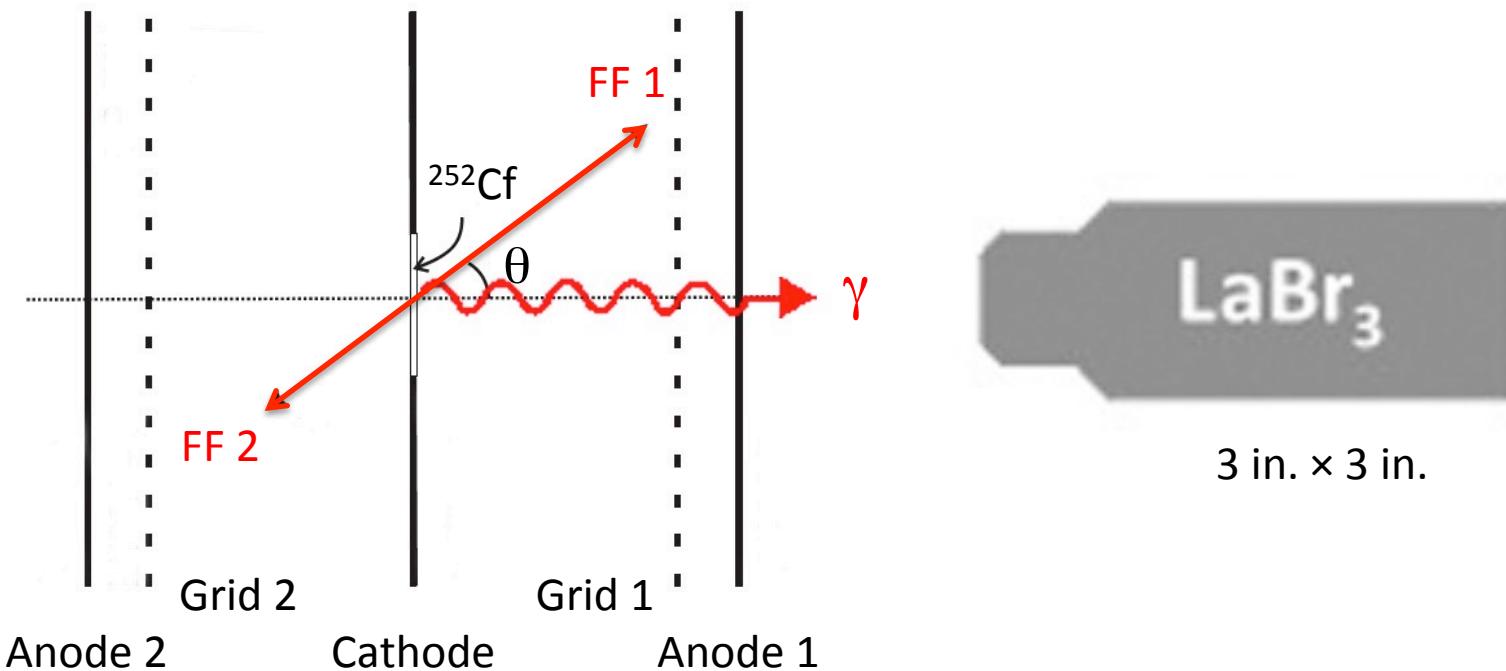
According to: Litaize & Serot, PRC 82, 054616 (2010)

Introduction

- For many years: precise measurement of prompt fission γ -ray spectra (PFGS)
- Determination of characteristics:
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 - Studies of dependence of A, Z, and E_x
 - Now: focus on the de-excitation process of fission fragments
 - Measurement of PFG angular distributions !

Experimental setup

Frisch grid ionization chamber + LaBr_3 detector



Correlations between fission fragments and γ -rays

Data treatment

Detector response matrix vs. transformation matrix

$$\begin{array}{c}
 \text{measured} \\
 \text{spectrum} \\
 \\
 \left(\begin{array}{c} y_1 \\ y_2 \\ \vdots \\ y_n \end{array} \right)
 \end{array}
 =
 \begin{array}{c}
 \text{response} \\
 \text{matrix} \\
 \\
 \left(\begin{array}{cccc} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ r_{n1} & & \cdots & r_{nn} \end{array} \right)
 \end{array}
 \begin{array}{c}
 \text{emission} \\
 \text{spectrum} \\
 \\
 \left(\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_n \end{array} \right)
 \end{array}$$

Data treatment

Detector response matrix vs. transformation matrix

measured spectrum response matrix emission spectrum

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ r_{n1} & \cdots & & r_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

usually simulated
(*GEANT4*,
PENELOPE)

Data treatment

Detector response matrix vs. transformation matrix

measured spectrum	response matrix	emission spectrum
----------------------	--------------------	----------------------

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ r_{n1} & \cdots & & r_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

 **diagonalized**

$$= \begin{pmatrix} r'_{11} & 0 & \cdots & 0 \\ 0 & r'_{22} & & \\ \vdots & \ddots & & \vdots \\ 0 & \cdots & 0 & r'_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

Data treatment

Detector response matrix vs. transformation matrix

measured spectrum response matrix emission spectrum

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & \vdots & & \vdots \\ r'_{n1} & \cdots & \cdots & r'_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

if both are known ...

diagonalized

$$= \begin{pmatrix} r'_{11} & 0 & \cdots & 0 \\ 0 & r'_{22} & & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 0 & r'_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

Data treatment

Detector response matrix vs. transformation matrix

measured spectrum response matrix emission spectrum

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ r_{n1} & \cdots & & r_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

$$= \begin{pmatrix} r'_{11} & 0 & \cdots & 0 \\ 0 & r'_{22} & & \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & 0 & r'_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

... this matrix can be determined, e.g. by
 $r'_{ii} = y_i / x_i$!

Data treatment

Detector response matrix vs. transformation matrix

measured spectrum	response matrix	emission spectrum
----------------------	--------------------	----------------------

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ r_{n1} & \cdots & & r_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

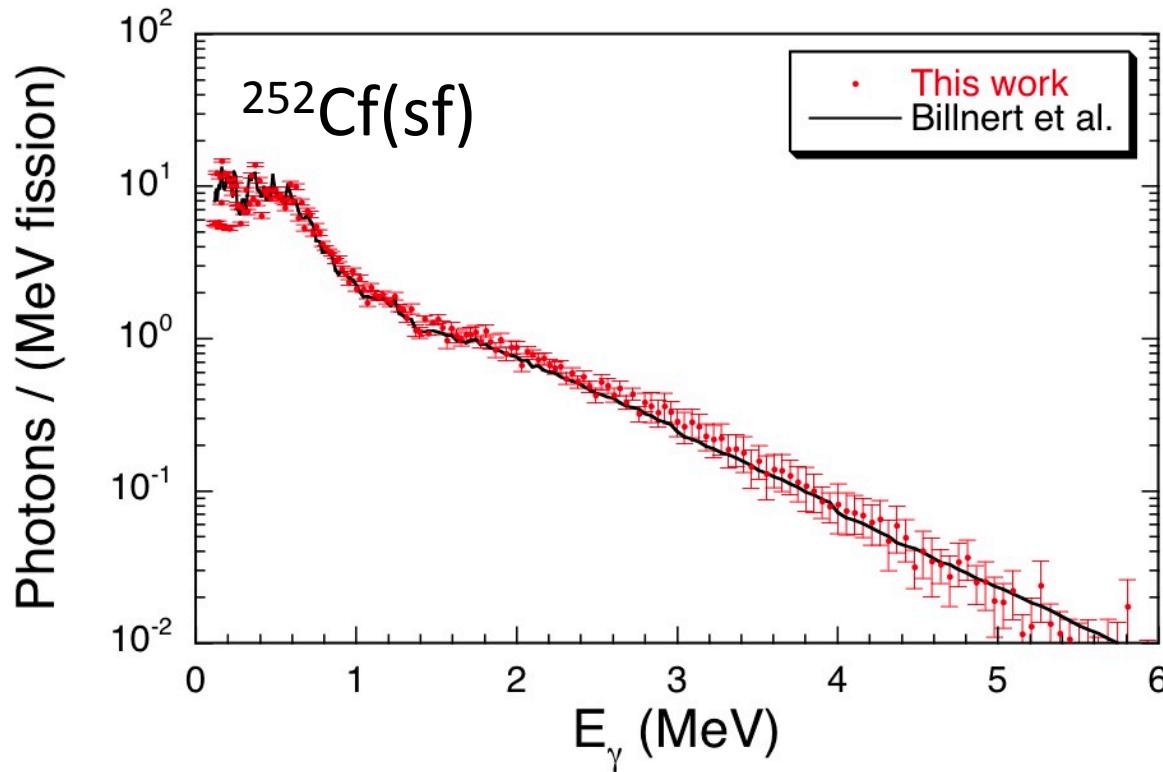
$$= \begin{pmatrix} r'_{11} & 0 & \cdots & 0 \\ 0 & r'_{22} & & \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & 0 & r'_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

... this matrix can be determined, e.g. by $r'_{ii} = y_i / x_i$!

Applied to other measurements (same conditions)!

Preliminary results

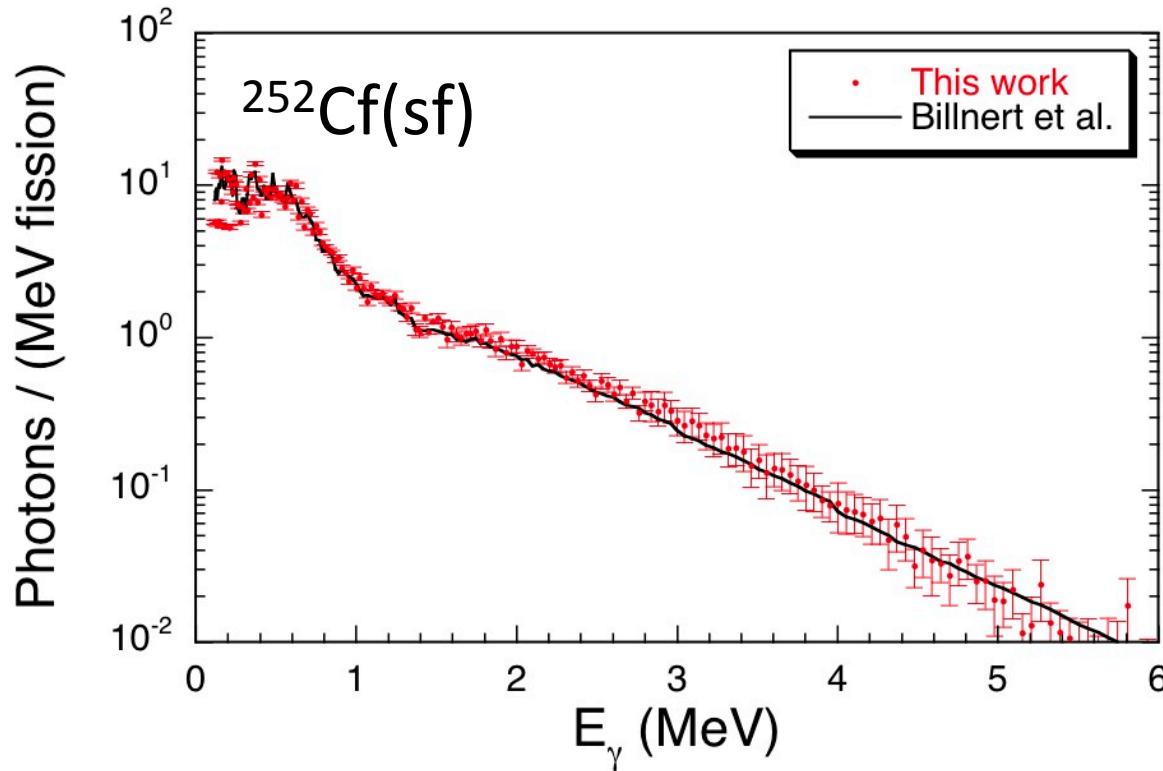
Prompt fission γ -ray spectra (PFGS)



Good agreement between this work and a previously measured spectrum

Preliminary results

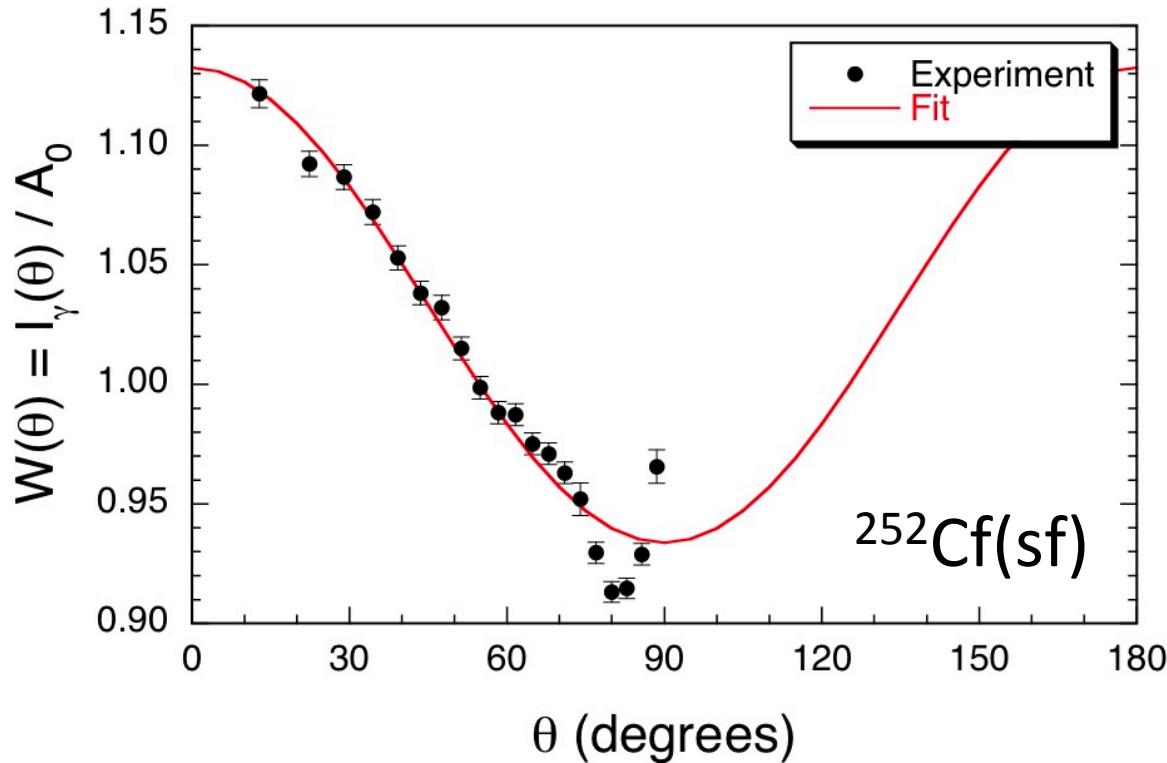
Prompt fission γ -ray spectra (PFGS)



Good agreement between this work and a previously measured spectrum → repeat for different $\cos\theta$ bins !

Preliminary results

Angular distribution

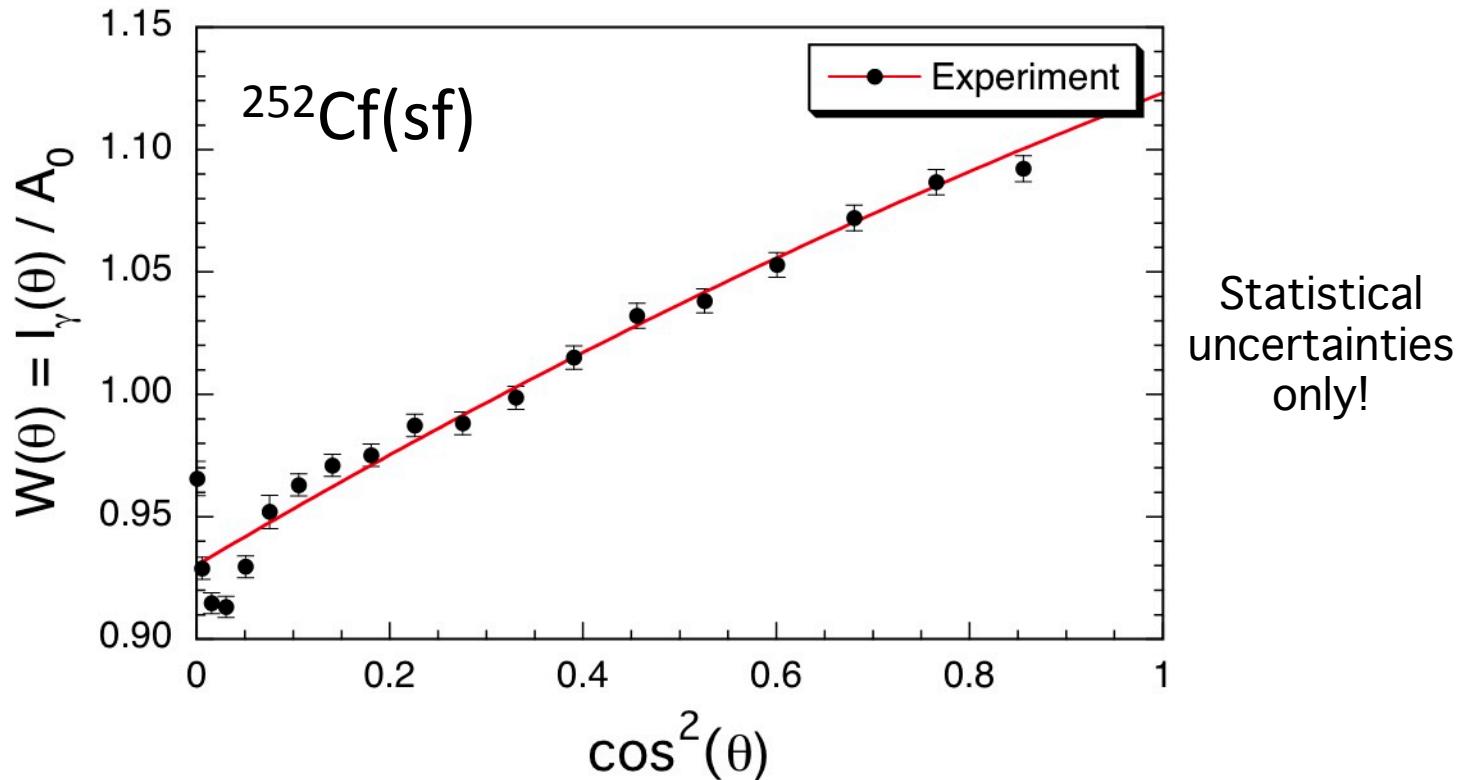


Statistical
uncertainties
only!

$$\text{Fit: } W(\theta) = A_0 [1 + \{A_2/A_0\}P_2(\cos\theta) + \{A_4/A_0\}P_4(\cos\theta)]$$

Preliminary results

Angular distribution

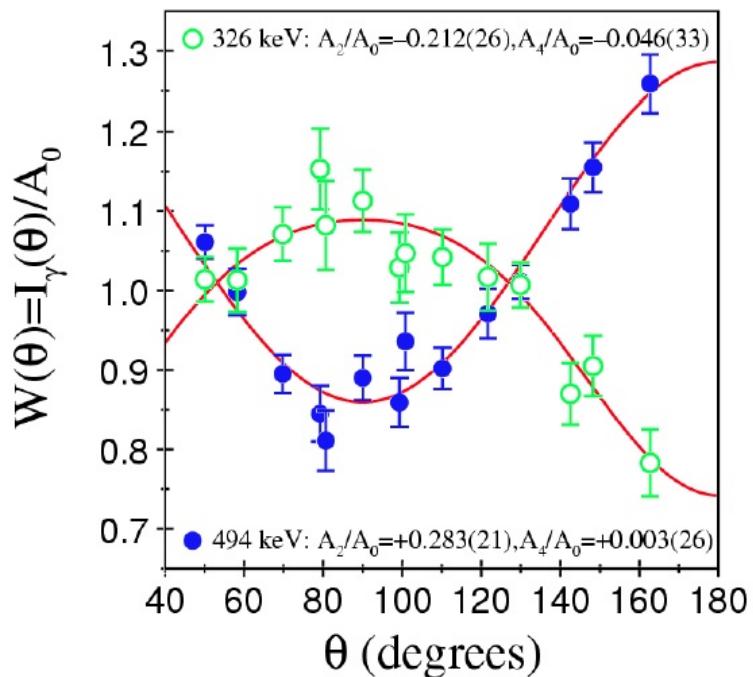


Fit result: $\{A_2/A_0\} = 0.13 \pm 0.03$

Preliminary results

Angular distribution

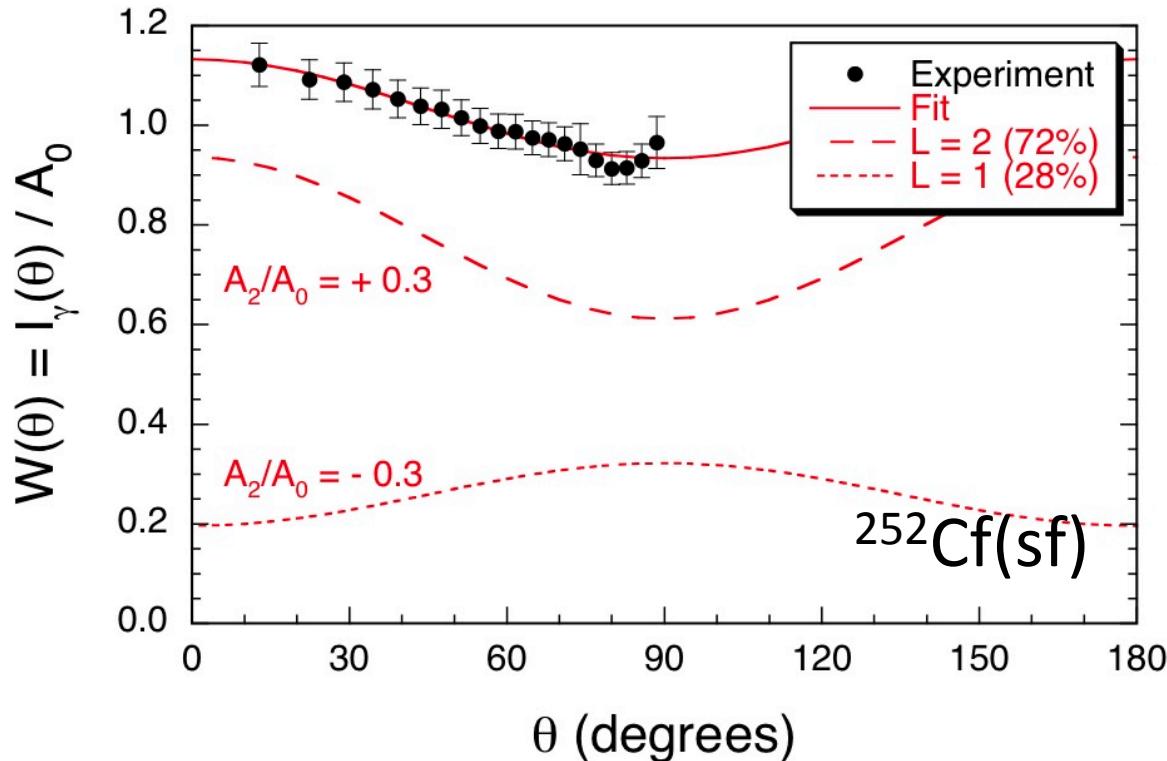
Angular Distributions in ^{109}Te



- Typically A_4/A_0 is close to zero
- And $A_2/A_0 \sim +0.3$ for a pure quadrupole ($\Delta I = 2$) transition
- Or $A_2/A_0 \sim -0.3$ for a pure dipole ($\Delta I = 1$) transition

Preliminary results

Angular distribution

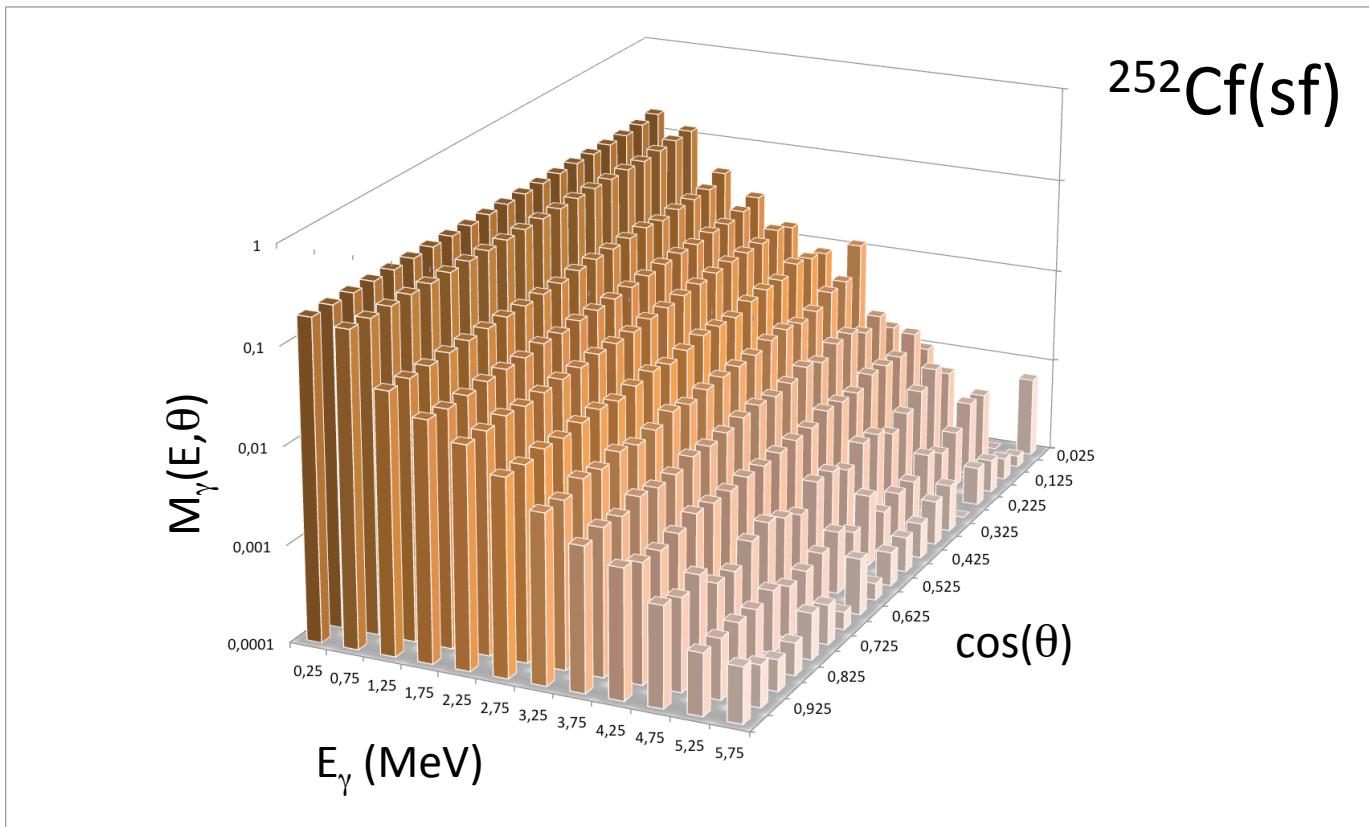


Statistical +
systematic
uncertainties!

Theory: $\{A_2/A_0\} = + 0.3$ for quadrupole radiation
 $\{A_2/A_0\} = - 0.3$ for dipole radiation

Preliminary results

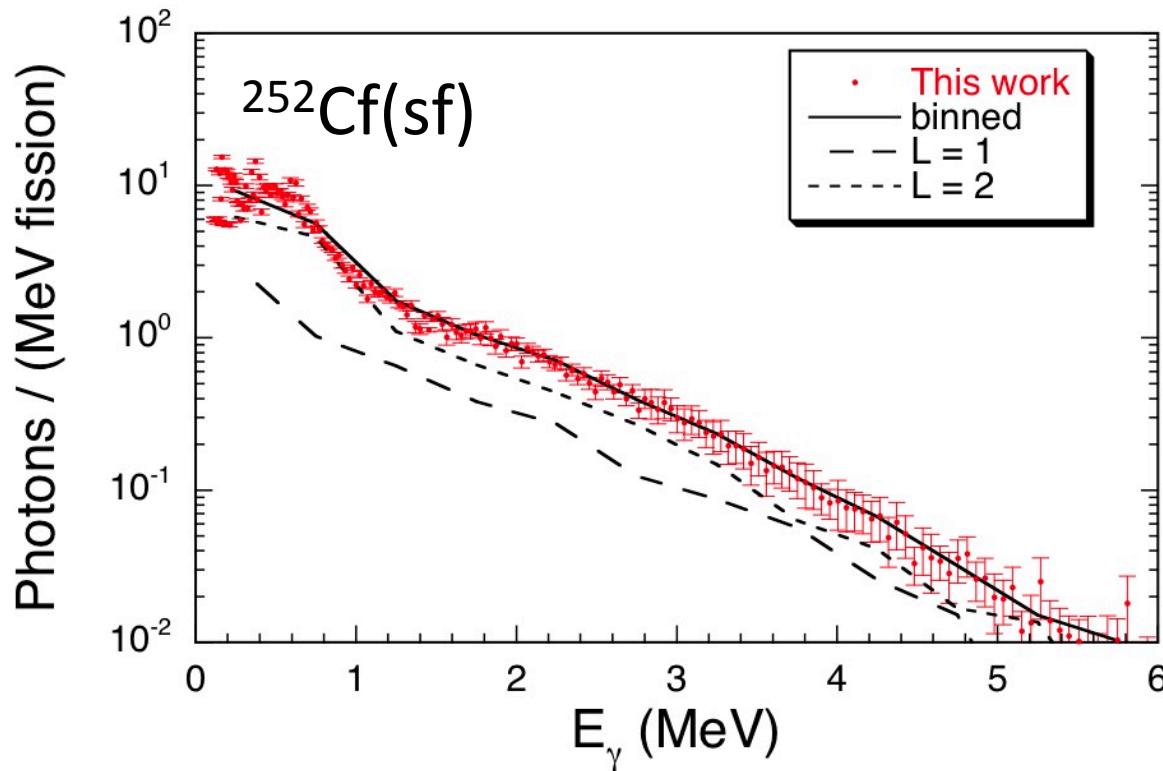
Angular distributions for 500 keV energy bins



- again: fit of Legendre polynomials
- decomposition of multipolarities $L = 1$ and 2

Preliminary results

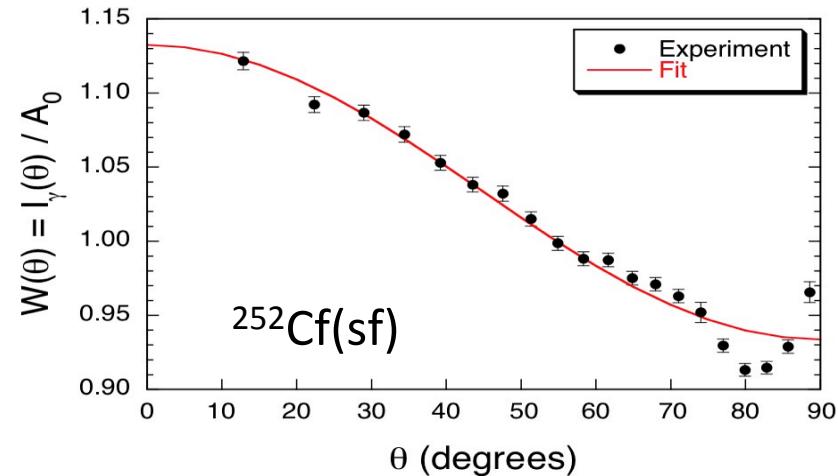
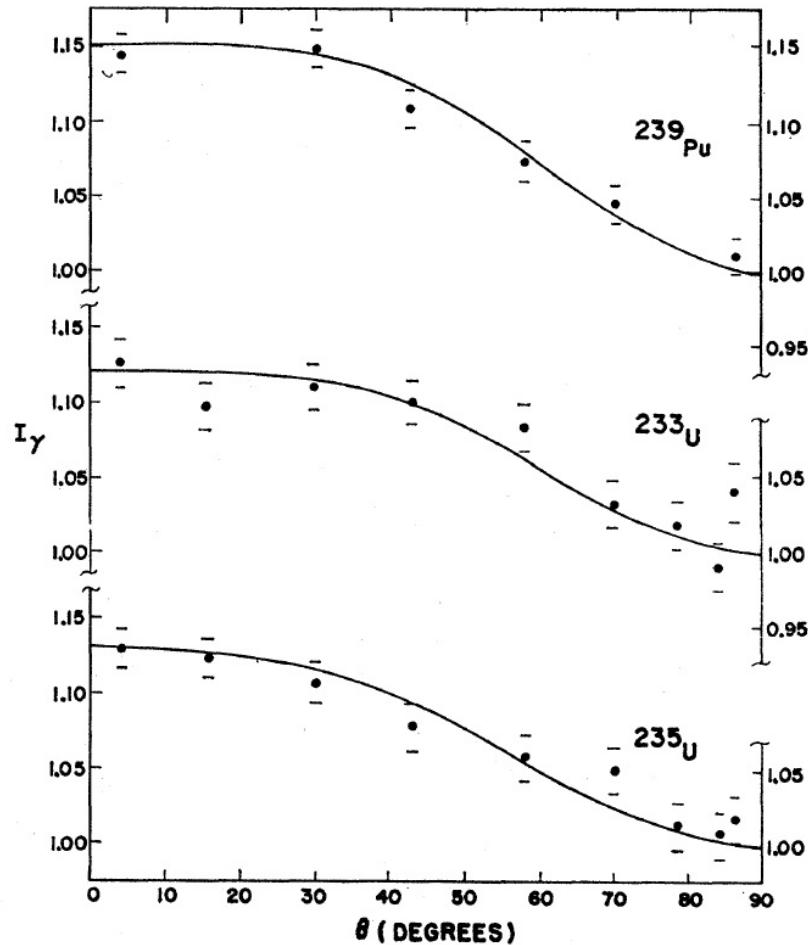
Multipolarity-dependent PFGS



- multipolarity-dependent spectra
- multipolarity-dependent PFGS characteristics

Discussion

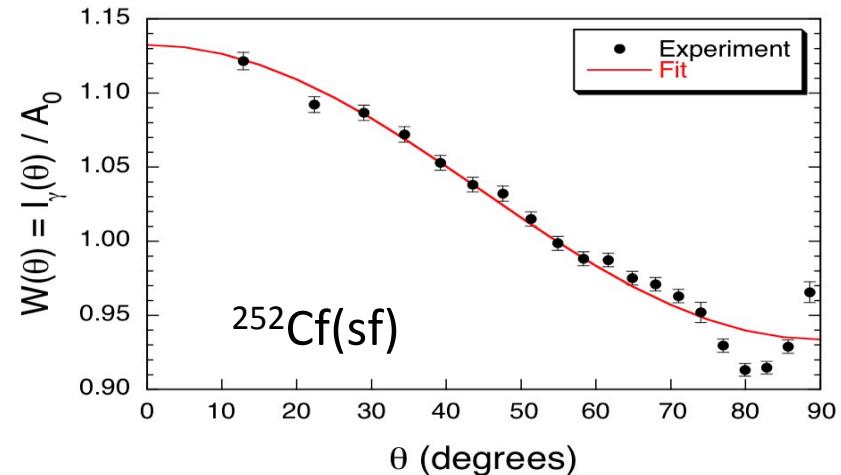
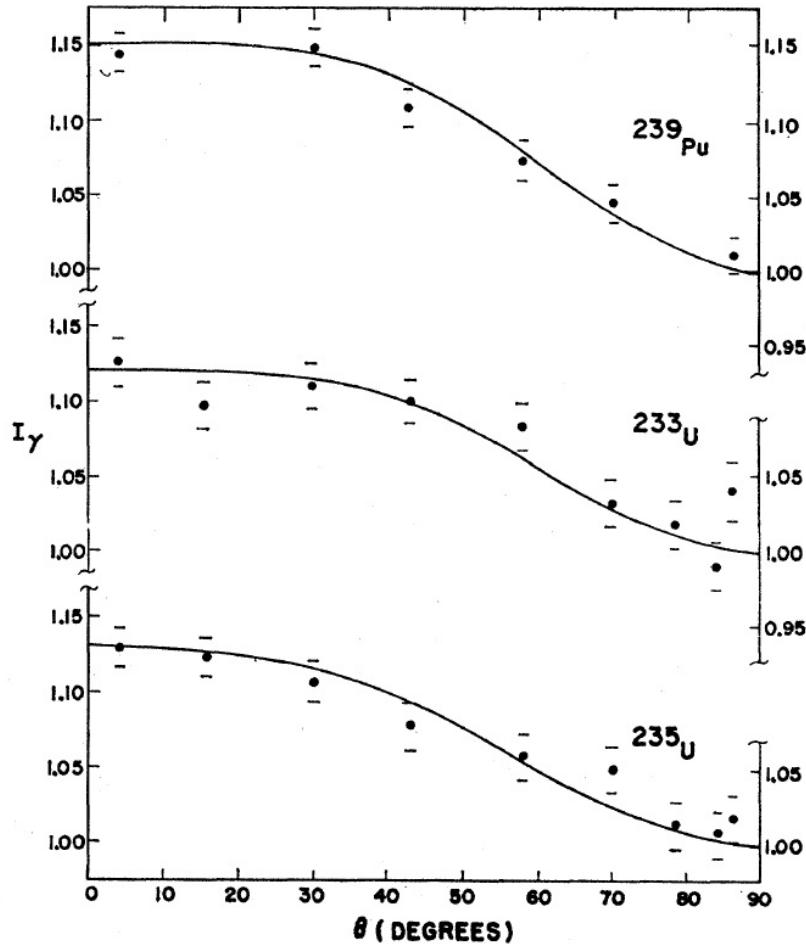
Previously measured angular distributions *)



*) Hoffman, Phys. Rev. 133 (1964)

Discussion

Previously measured angular distributions *)

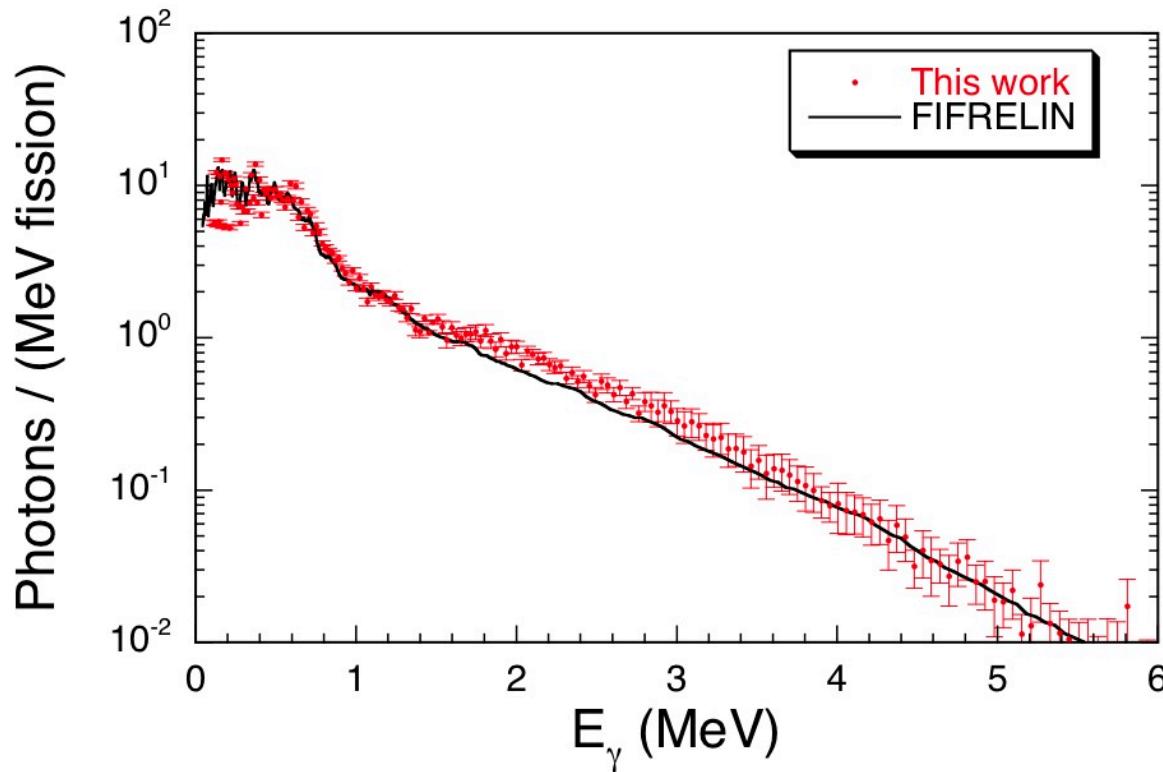


Good agreement
in dominating E2
character !

*) Hoffman, Phys. Rev. 133 (1964)

Discussion

Comparison with FIFRELIN calculations *)

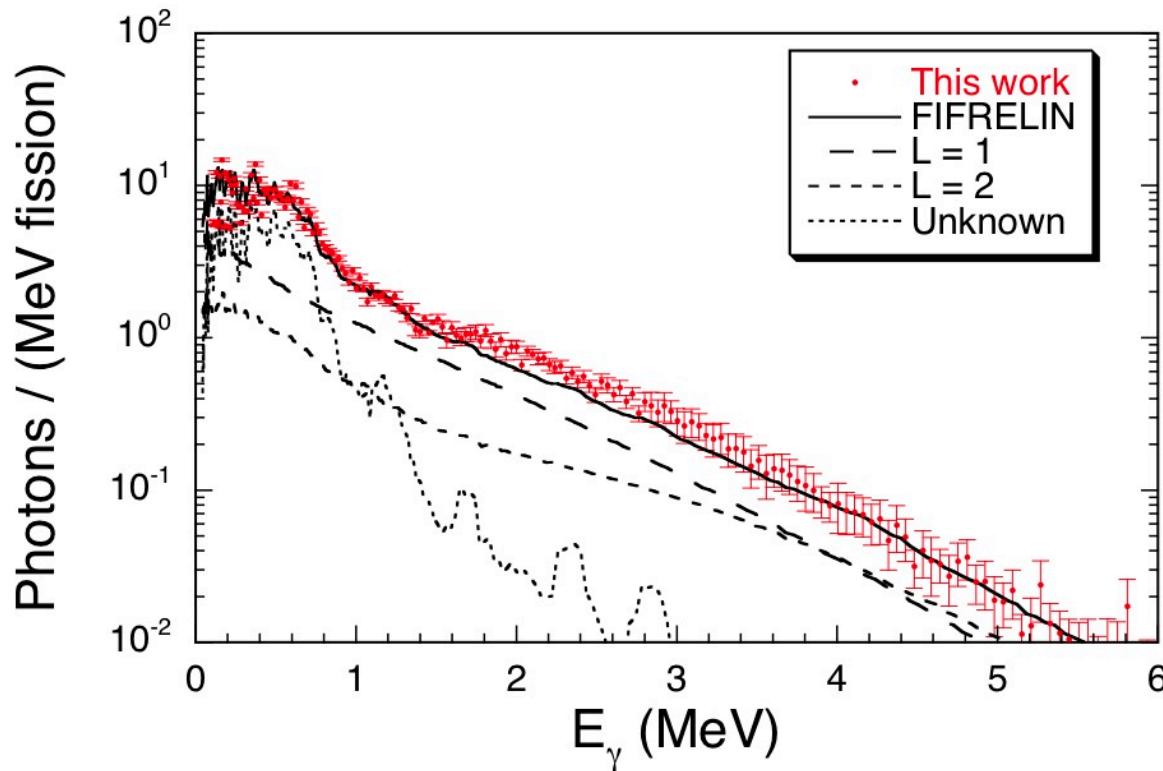


*) A. Chebboubi,
priv. comm.

Good agreement between integral spectra!

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Good agreement between integral spectra!

But **FIFRELIN** also provides multipolarity-dependent PFGS.

Discussion

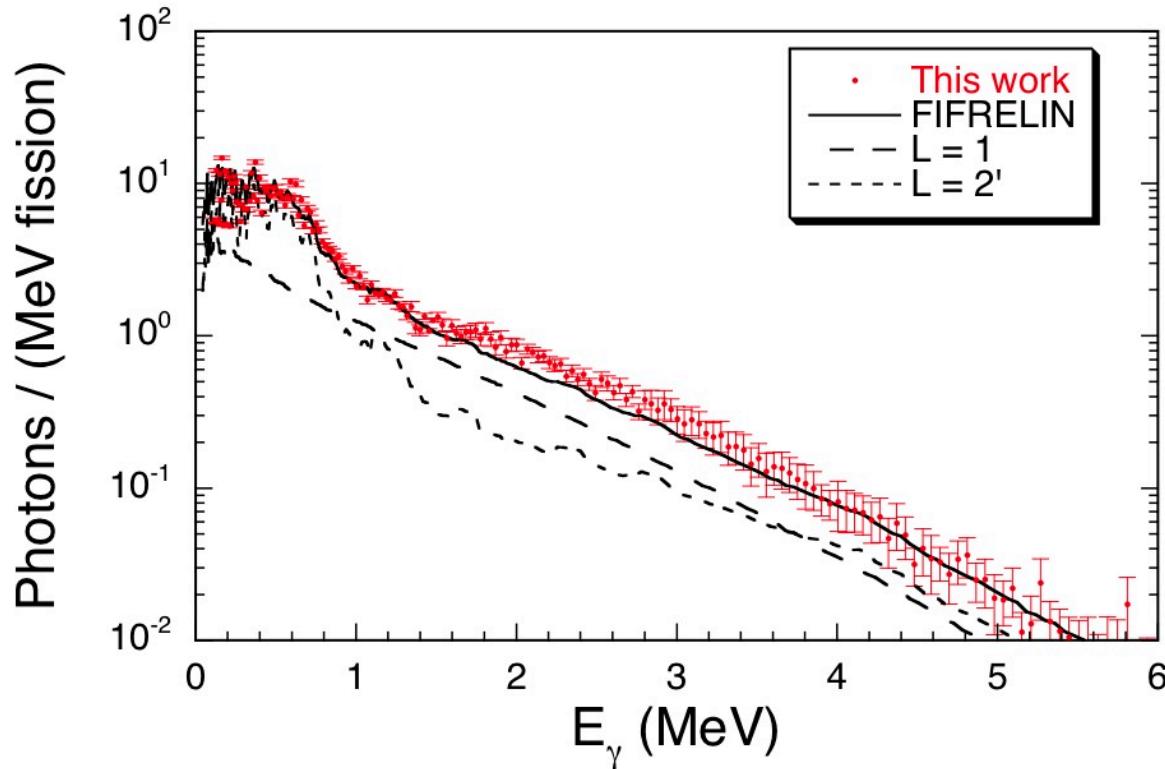
Comparison with FIFRELIN calculations *)

	Experiment (this work)	Calculations (FIFRELIN)	
\bar{M}_γ	8.28 ± 0.51	8.28	(adjusted)
\bar{M}_γ (L = 1)	2.31	(28 %)	3.20
\bar{M}_γ (L = 2)	5.97	(72 %)	1.45
\bar{M}_γ (unknown)	---		3.63
$\bar{\epsilon}_\gamma$	0.79 ± 0.10 (MeV)	0.76	(MeV)
$\bar{\epsilon}_\gamma$ (L = 1)	0.86	(MeV)	0.94
$\bar{\epsilon}_\gamma$ (L = 2)	0.76	(MeV)	1.03
$\bar{\epsilon}_\gamma$ (unknown)	---		0.50
\bar{E}_γ	6.51 ± 0.76 (MeV)	6.30	(MeV)
\bar{E}_γ (L = 1)	1.99	(MeV)	3.00
\bar{E}_γ (L = 2)	4.52	(MeV)	1.49
\bar{E}_γ (unknown)	---		1.81

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Discussion

Comparison with FIFRELIN calculations *)



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From our observations: unknown transitions $\rightarrow L = 2$,
 $L = 2 + \text{unknown} \rightarrow L = 2'$.

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\bar{M}_γ	8.28 ± 0.51	8.28	(adjusted)
\bar{M}_γ (L = 1)	2.31	(28 %)	3.20
\bar{M}_γ (L = 2')	5.97	(72 %)	5.08
\bar{M}_γ (unknown)	---		---
$\bar{\epsilon}_\gamma$	0.79 ± 0.10 (MeV)	0.76	(MeV)
$\bar{\epsilon}_\gamma$ (L = 1)	0.86	(MeV)	0.94
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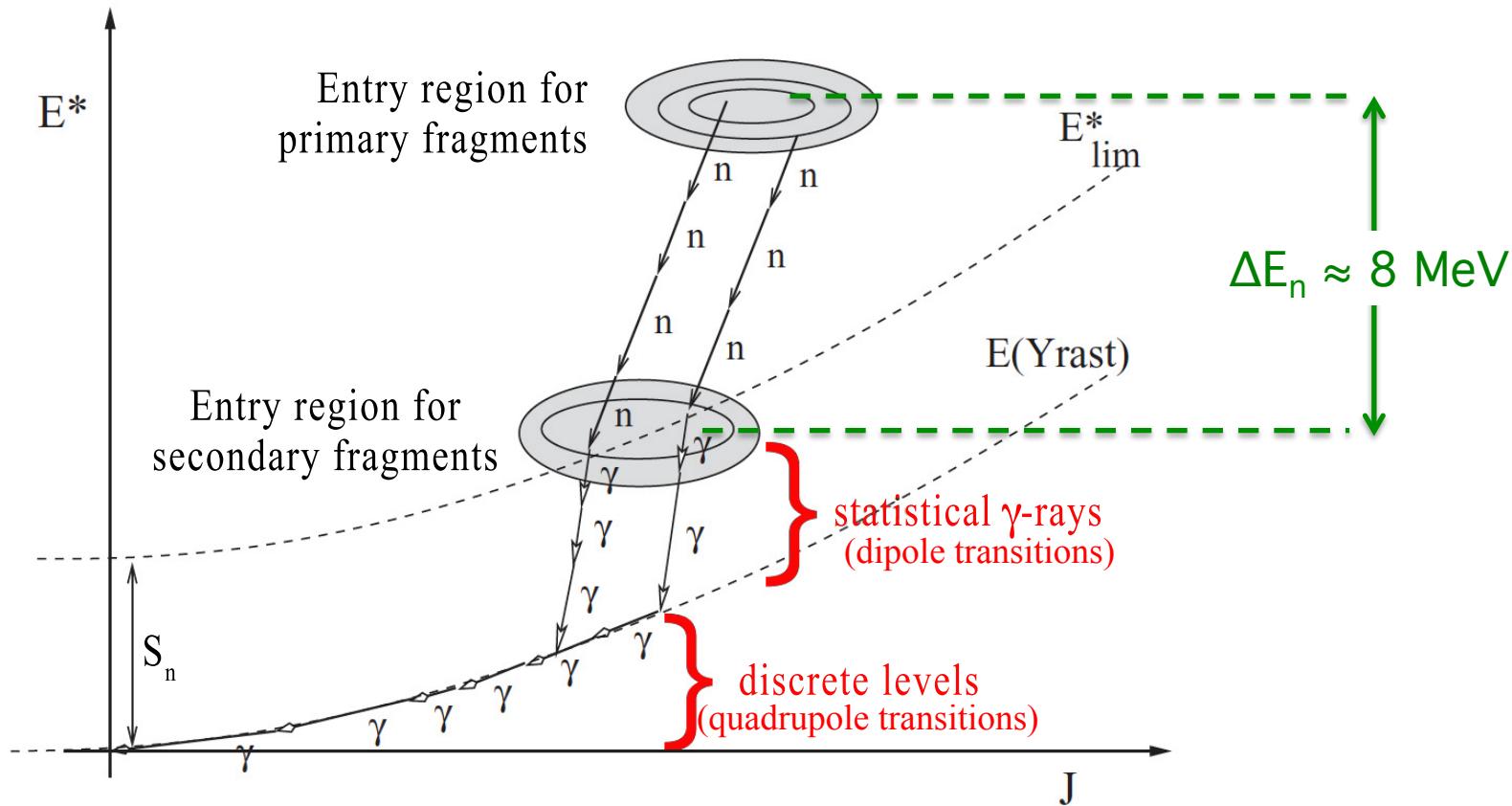
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Summary

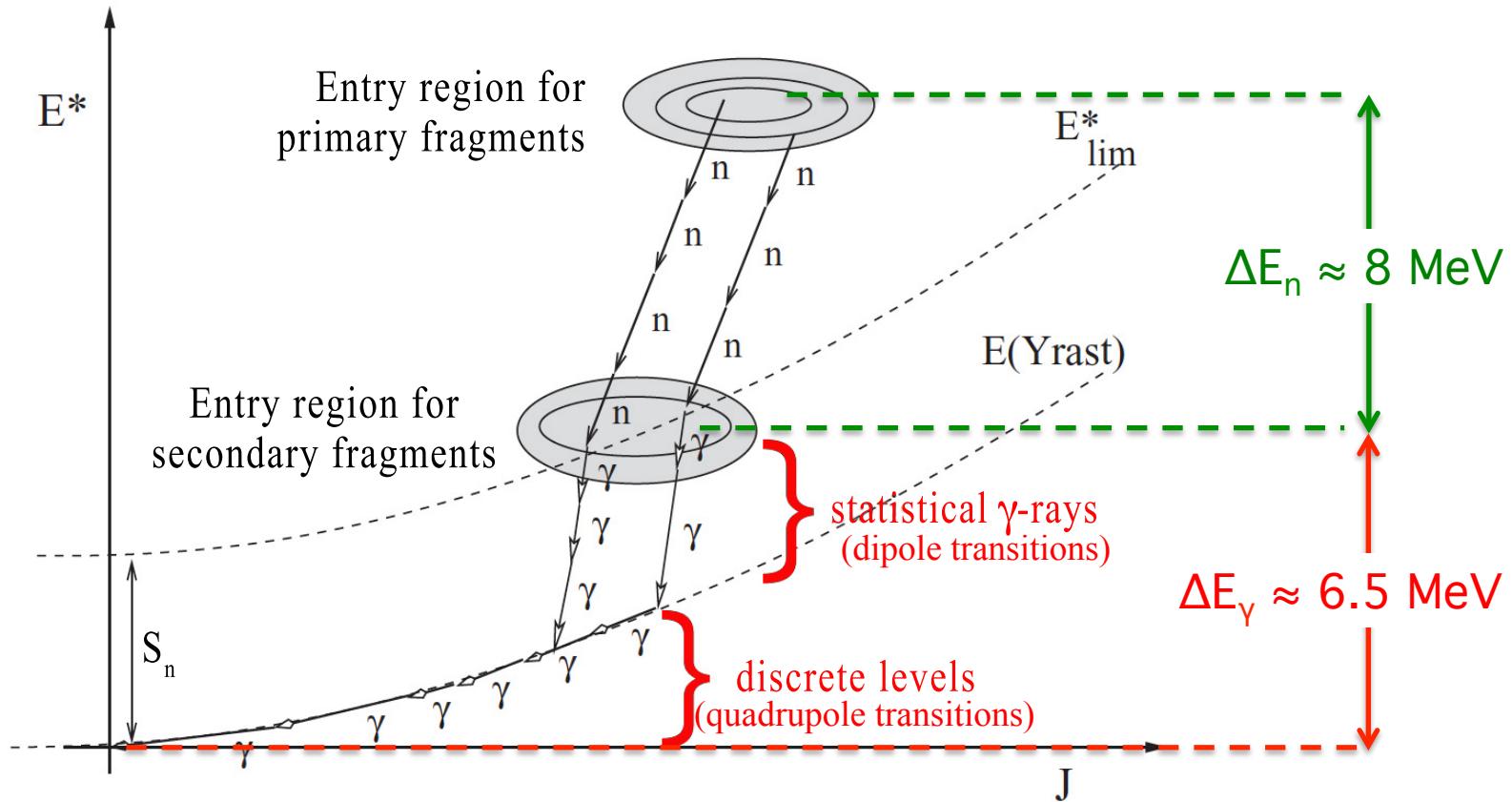
- Measured angular distribution of prompt γ rays from $^{252}\text{Cf}(\text{sf}) \rightarrow$ dominant E2 character, in good agreement with previous measurements
- With $\langle M_\gamma \rangle \approx 8.3$ follows
 - $\langle M_{\gamma, L=1} \rangle \approx 2.3$ and $\langle M_{\gamma, L=2} \rangle \approx 6.0$

Summary

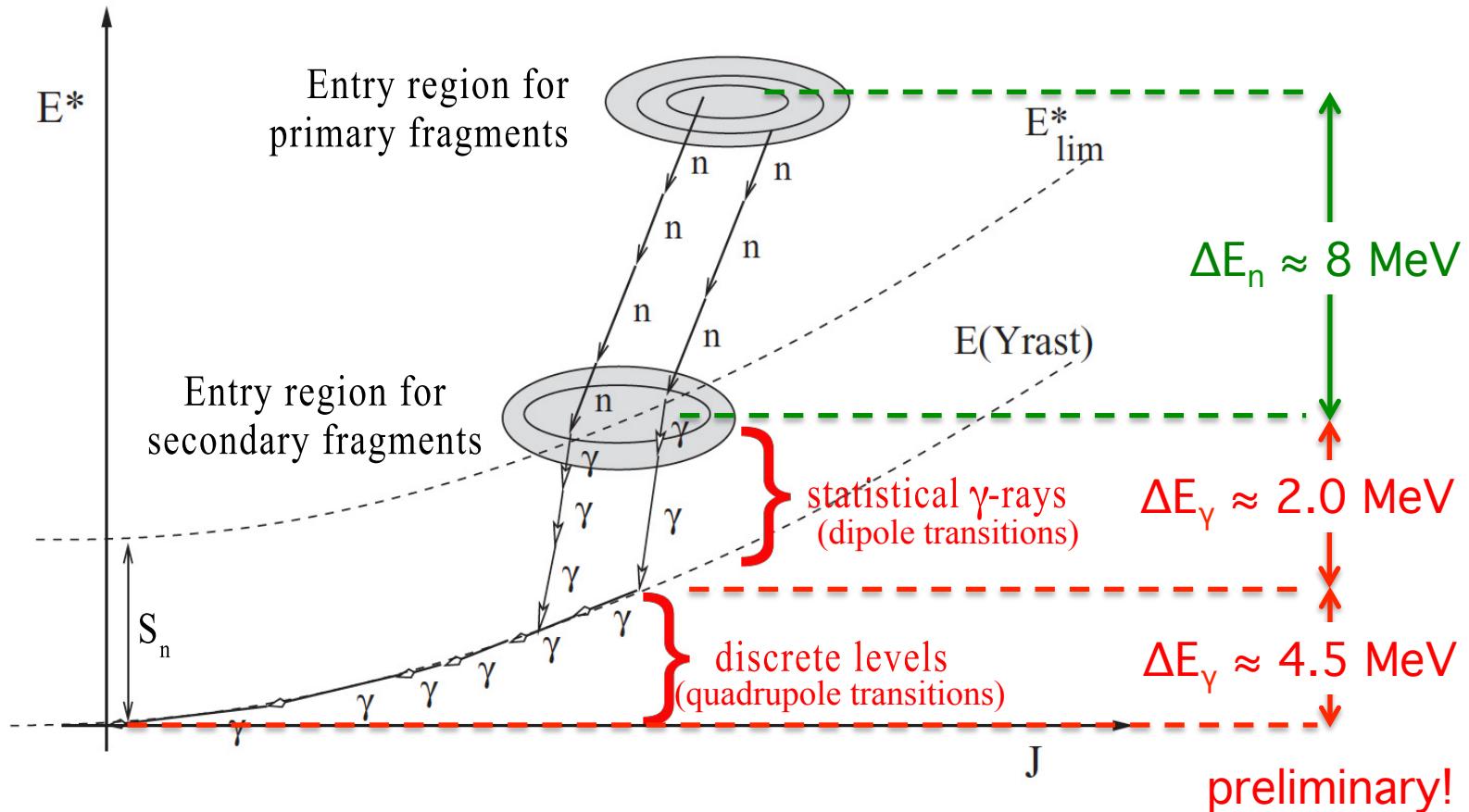
Sequential emission of neutrons and γ -rays



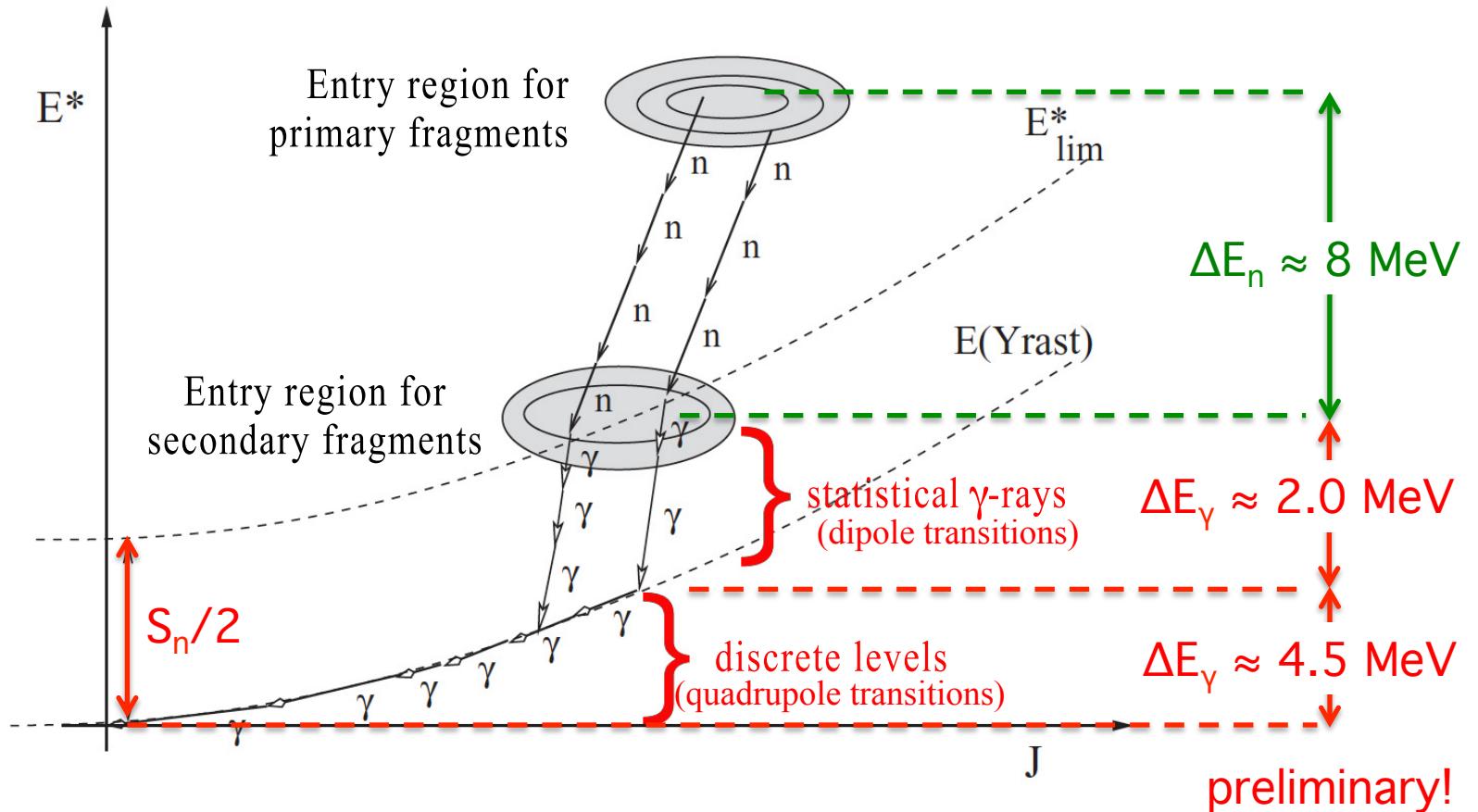
Summary



Summary



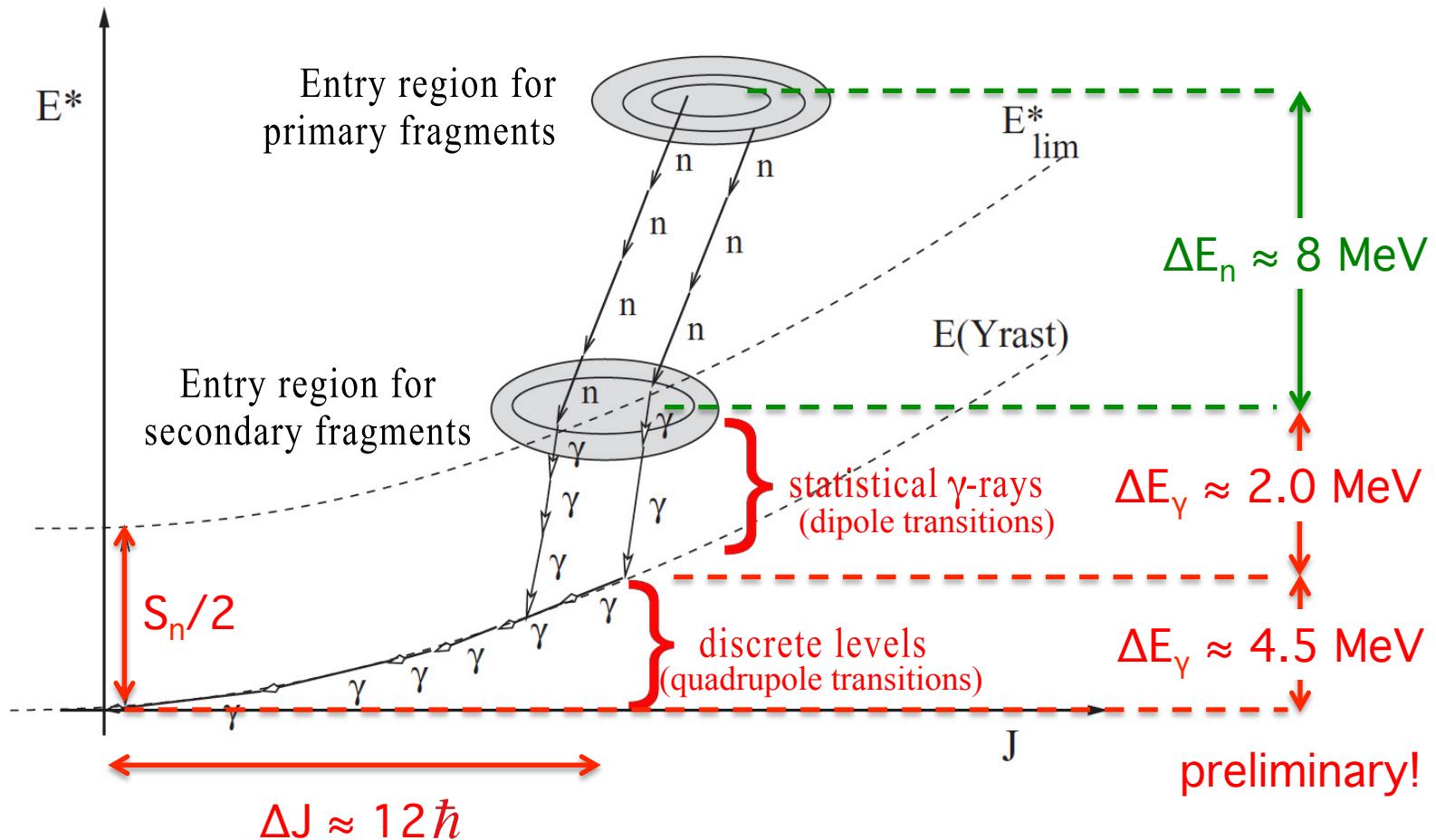
Summary



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 - $\langle M_{\gamma, L=1} \rangle \approx 2.3$ and $\langle M_{\gamma, L=2} \rangle \approx 6.0$
- Average spin of fission fragments is $J \approx 12 \hbar$, which seems a bit high, but still reasonable
- Comparison with FIFRELIN calculations shows rather good agreement ...

Outlook

- ... that is even better with a more realistic (?) assumption $\{A_2/A_0\} \approx -0.2$ for dipole radiation,
- leading to
 - $\langle M_{\gamma,L=1} \rangle \approx 2.8$ (34 %) and
 - $\langle M_{\gamma,L=2} \rangle \approx 5.5$ (66 %)
- These results have to be compared with other related information on fission fragments, such as
 - average neutron separation energies
 - average moments of inertia etc.

The collaborators

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Thank you!